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LAND USE IN LCA

Development of a soil compaction indicator in life cycle assessment

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Abstract
Purpose Integrating soil quality impacts in life cycle assessment (LCA) requires a global approach to assess impacts on soil quality that can be adapted to individual soil and climate contexts. We have developed a framework for quantifying indicators of impact on soil quality, valid for all soil and climate conditions, and considering both on-site and off-site agricultural soils. Herein, we present one of the framework's impact indicators, which has not yet been quantified in detail in LCA studies: soil compaction.
Material and methods The method includes guidelines and tools for estimating midpoint compaction impacts in topsoil and subsoil as a loss of soil pore volume (in cubic metre per functional unit). The life cycle inventory (LCI) and life cycle impact assessment are based on simulation modelling, using models simple enough for use by non-experts, general enough to be parameterised with available data at a global scale and already validated. Data must be as site specific and accurate as possible, but if measured data are missing, the method has a standardised framework of rules and recommendations for estimating or finding them. The main model used, COMPSOIL, predicts compaction due to agricultural traffic. Results are illustrated using a case study involving several crops in different soil and climate conditions: a representative pig feed produced in Brittany, France.
Results and discussion Predicted compaction impacts result from the combination of site-specific soil, climate and management characteristics. The data necessary to the LCI are readily available from free soil and climate databases and research online. Results are consistent with compaction observed in the field. Within a soil type, predictions are most sensitive to initial bulk density and soil water content.
Conclusions The method lays the foundation for possible improvement by refining estimates of initial soil conditions or adding models that are simple and robust enough to increase the method's capacity and accuracy. The soil compaction indicator can be used in LCAs of bio-based materials and of waste management stages that consider composting. The framework includes other operational indicators (i.e. water erosion, soil organic matter change) to assess impact on soil quality. They complement other impact categories, providing increased ability to identify "impact swapping".

Keywords Compaction · Indicators · Life cycle assessment · Soil quality

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1 Introduction

Soils are an essential component of the global ecosystem, as important as the hydrosphere and atmosphere for ecosystem functioning, that are subject to a series of threats in the form of degradative processes (EU 2006). The sustainable development of human activities, in particular agriculture and the production of bio-based materials (e.g. food, biofuels, wood, textile, paper), requires the maintenance of soil quality. Soil quality can be defined by a soil's capacity to function (Karlen et al. 1997) and/or its fitness for a given use (Larson and Pierce

1994; Letey et al. 2003), both of which are influenced by activities that directly or indirectly impact soil properties.

Soil compaction, a major process of soil degradation around the world (Oldeman et al. 1991), is the decrease in soil volume, in particular the air-filled fraction (Hillel 1998). It alters the spatial arrangement, size and shape of clods and aggregates and, consequently, the pore spaces both inside and between them (Defossez and Richard 2002). It can be expressed by bulk density, pore volume, porosity, void ratio or soil strength. Compaction is one of the eight threats to soil identified in the Thematic Strategy for Soil Protection in Europe (Huber et al. 2007) but also concerns soils on other continents (reviewed by Hamza and Anderson 2005). Compaction is found in all systems of land use in which land is crossed by machines, people, livestock or wildlife and is a major concern in agriculture (Batey 2009). The degree of compaction depends not only on the amount and surface area of pressure applied, but on the water content and weight-bearing capacity of the soil at the time. Compaction alters soil structure, limits water and air infiltration and impedes root penetration. Ultimately, compaction can influence soil chemical and biological processes (e.g. N and C cycles, greenhouse gas emissions), plant growth and yield and soil biodiversity. Topsoil compaction in hilly landscapes increases runoff and may increase erosion, with subsequent on- and off-farm environmental impacts. It is a cumulative process; additional machine passes, for example, may increase compaction when soil water content is high (Bakker and Davis 1995). Since it is relatively reversible with ploughing, topsoil compaction is related more to shorter term economic and environmental impacts, whereas subsoil compaction, difficult to reverse even with subsoiling, concerns longer term sustainability. In the context of this work, we accept the following definition for soil: “the naturally occurring, unconsolidated mineral or organic material at least 10 cm thick that occurs at the earth’s surface and is capable of supporting plant growth” (SCWG 1998). This definition excludes artificially displaced materials (e.g. mine spoils) but includes those subject to soil-forming processes. Nonsoil is the superficial materials that do not meet the preceding definition of soil.

Until recently, impacts of production systems on soil quality have not been explicitly included in life cycle assessment (LCA) (Brandão et al. 2011) despite recommendations to do so (Milà i Canals et al. 2007a; 2007b). Although a scarce resource, soil has been treated as an “ancillary” item when estimating land use impacts in LCA, contributing to the maintenance of production processes but not part of them (Fava et al. 1990). When impacts on soil become the subject of study, the soil must be included within LCA system boundaries, which means considering the state of the soil, not only its inputs and outputs, when estimating impacts. Consideration of system state already exists in LCA for indicators of impacts on water resources (Pfister et al. 2011) and biodiversity (Curran et al. 2011).

In a previous paper (Garrigues et al. 2012), we addressed the challenges of integrating an indicator of impacts on soil quality into the methodological structure of LCA. Impacts on soil quality in LCA are more easily expressed by processes than by physical, chemical or biological properties and functions because processes are easier to relate to functional units. Erosion and soil organic matter (SOM) impacts already exist in LCA approaches (Milà i Canals et al. 2007a; Nuñez et al. 2010), but compaction impacts have received relatively little attention. Cowell and Clift (2000) proposed a “soil compaction indicator” for agricultural subsoil that equalled the product of the mass of field machinery and the time they spend in the field (i.e. potential impact in tonne-hours). Although the indicator did not consider the compactability of soil, the authors mentioned that it could be included (analogous to a fate factor for toxicity impacts). More recently, Oberholzer et al. (2012) proposed the Swiss Agricultural Life Cycle Assessment - Soil Quality method (SALCA-SQ) for including on-farm soil quality in LCAs. One of SALCA-SQ’s nine qualitative indicators assesses the influence of a given cropping system on soil macropore volume. It is a function, among other factors, of subsoil compaction risk, itself a function of the greatest single-axle pressure exerted by each machine (at a depth of 35 cm), its area of contact, soil firmness and soil water content on operation dates (Oberholzer et al. 2006). Compaction risk scores (from 0 to −2) from all machines and plots are added together to estimate farm-scale compaction risk. Its predictions of soil quality impacts of experimental organic and conventional crop rotations appear largely consistent with field observations (Oberholzer et al. 2012). SALCA-SQ, however, is designed to consider soil quality impacts of entire cropping systems, not those of the products they produce or of products containing several crop-based ingredients (potentially from different farms around the world). For it to do so would require a significant amount of work, since SALCA-SQ is highly oriented and calibrated for Swiss conditions (e.g. in its lookup tables). In addition, its qualitative scale of impact (−−, −, 0, +, ++) has the potential to render it relatively insensitive to differing impacts of agricultural practices.

To address some of these issues, we developed a method to quantify soil compaction impacts of agricultural products in an LCA context that aims to be valid for all soils and climates that considers both on-site and off-site (upstream) agricultural soils. It brings together existing water balance and soil compaction models in a way that can be reasonably applied in LCA context. It takes into account the types and dates of field operations, machine mass and tyre width, the surface area affected and soil characteristics. Data

requirements are modest, allowing the method to be applied to products with multiple agricultural ingredients. We applied the method to a case study of a feed produced for pigs raised in Brittany, France.

2 Methods

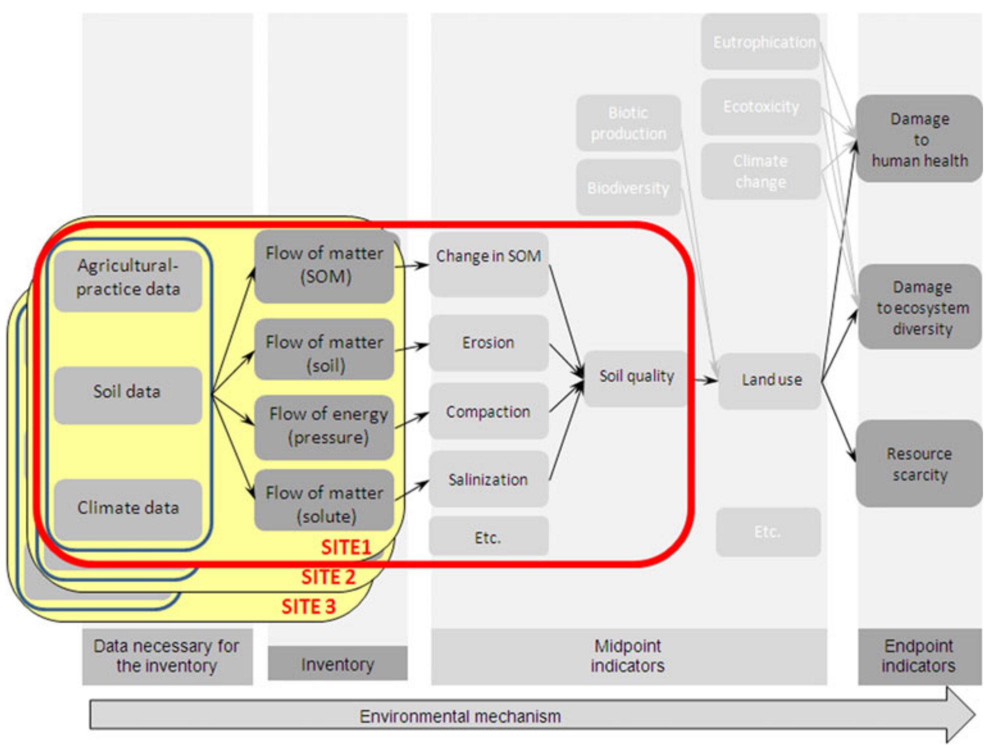
2.1 General framework of the method

Soil quality impacts are quantified with midpoint impact indicators describing processes that can degrade or improve the soil. Pathways were selected to link elementary flows of the inventory (LCI) to the midpoint indicators, which result from the combination of soil, climate and management characteristics (Fig. 1). The LCI and life cycle impact assessment (LCIA) are based on simulation modelling, using models simple enough for use by non-experts, general enough to be parameterised with available data for any location on Earth and already tested and validated for certain scenarios and soils. Input data must be as site specific and accurate as possible, but if measured data are missing, the method has a standardised framework of rules and recommendations for estimating or finding them. Most of the input data necessary for establishing the LCI are common to the first three midpoint indicators (i.e. water erosion, SOM change and compaction) (Corson 2012). For each indicator, total impact is estimated by summing the impacts from individual upstream agricultural sites together. Thus, the method currently has no regionalised characterisation factors for the LCIA, assuming that a given degree of erosion, SOM or compaction has equal impact regardless of location. For each crop, the temporal boundary includes the inter-crop period (if any) that occurs just before the crop. For perennial crops, impacts of planting are divided over the productive lifetime of the crop to obtain a dimension of 1 year. The system boundary for crop products used as raw ingredients is set at the farm gate, while that for products made from these ingredients is set at the factory gate.

2.2 Soil compaction indicator

The process to estimate compaction impact for an agricultural production system requires several steps (Fig. 2). First, data on machine operations (e.g. operation types and dates, machine mass and tyre dimensions) for 1 ha and 1 year of crop production are acquired (Electronic Supplementary Material, Table 1). Next, soil water content on the dates of field operations is estimated. Soil water models require knowledge of soil properties that vary spatially and temporally and are difficult to measure. Thus, the method uses a simple water balance model with two reservoirs (BILHY for BILan HYdrique, Electronic Supplementary Material, Table 2) to calculate the total soil water content to a depth of 50 cm (Jacquart and Choisnel 1995). The predicted soil water content is assumed to be constant from 0 to 50 cm, as

Fig. 1 Conceptual steps for assessing impacts on soil quality (*outlined*) (adapted from Garrigues et al. 2012). Not all potential links between midpoint indicators are shown



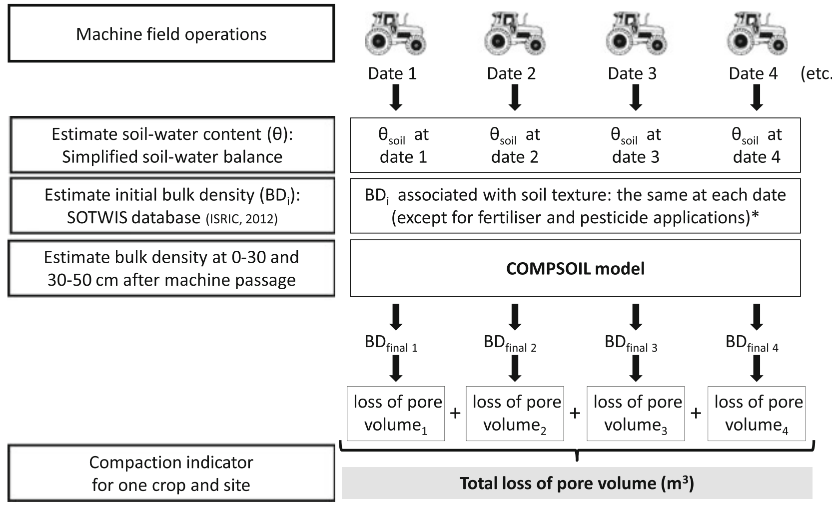


Fig. 2 Operational procedure for estimating compaction impact (loss of pore volume). *Asterisk*: For fertiliser and pesticide applications, each subsequent pass begins with the final bulk density profile predicted after the previous pass

the consideration of different horizons (i.e. topsoil vs. subsoil) did not increase the accuracy of predictions of soil water content in a study by Al Majou et al. (2008). Input data include daily temperature, precipitation and solar radiation, which can be acquired from international climate databases (NASA 2012). For greater precision, the time step of BILHY was decreased from 10 days to 1 day. BILHY requires estimates of potential evapotranspiration, which we estimated with the TURC method (Federer 1996). Then, initial soil bulk density is estimated as a function of soil texture. Initial dry bulk density comes from the SOTWIS database (ISRIC 2012), from which soil texture is divided into five classes (coarse to very fine, according to the FAO texture triangle), each associated with an initial bulk density (Table 1).

Next, the COMPSOIL model (O'Sullivan et al. 1999; Défossez et al. 2003) is used to predict bulk density after each machine operation using readily available mass and tyre data. The depth to which compressive forces are transmitted depends on soil moisture, bulk density and machine characteristics. For simplicity, the method assumes uniform initial bulk density and water content profiles. Simulations begin with the same initial bulk density for all field operations, which implies that machines do not follow the same tracks each time. An exception is made, however, for fertiliser and pesticide applications, which tend to follow the same tracks; in this case, each subsequent pass begins with the final bulk density profile predicted after the previous pass. The passage of ploughs is

Table 1 Mean dry bulk density (ρ_s) of texture classes of the FAO texture triangle calculated from the SOTWIS database (ISRIC 2012). Mean ρ_s is used as initial bulk density in the COMPSOIL model

Texture	Coarse	Medium	Medium fine	Fine	Very fine
Mean ρ_s	1.41	1.35	1.29	1.30	1.25
n	474	1,625	182	3,011	1,519

assumed to result in no increase in soil compaction from 0 to 30 cm; only predicted compaction below 30 cm is considered. COMPSOIL predicts final bulk density every 5 cm from 0 to 50 cm deep. Mean topsoil (0–30 cm) and subsoil (30–50 cm) final bulk densities are calculated separately.

The increase in mean dry bulk density is converted into a loss of pore volume (Δf in cubic metre):

$$\Delta f = (f_f - f_i) \times A_{aff} \times D, \tag{1}$$

where f_f and f_i are the final and initial porosity, respectively (in percent), A_{aff} the affected area (in square metre) and D soil depth (in metre)

$$f = \frac{p_s - p_b}{P_s} = 1 - \frac{p_b}{p_{s,}} \tag{2}$$

$$p_b = 2.65 \times (1 - f), \tag{3}$$

where ρ_b is the dry bulk density, ρ_s particle density=2.65 t/m^3 and f the porosity (in percent).

$$A_{aff} = T_{w\ max} \times \left(\frac{100}{W_w}\right) \times 2, \tag{4}$$

where $T_{w\ max}$ is the width of the widest tyre of the machine operation system (in metre) and W_w the fieldwork width (in metre), which is needed to calculate the number of 100-m passes in a square 1-ha field.

For each operation, topsoil and subsoil losses of pore volume are added together to equal the total loss of pore volume for the operation. Finally, the losses of pore volume of all operations are added together to obtain the total loss per hectare of crop, which is the value used for LCI and LCIA. Loss of pore volume is estimated for crop-based products by dividing the impact per hectare by the dry matter yield per

hectare. Loss of pore volume for co-products made from raw crop products (e.g. soya oil and meal) is calculated as usual, allocating impacts to co-products when necessary.

2.3 Case study

The case study was selected to illustrate impacts of a composite product formed from crop-based ingredients produced in and with widely differing soils, climates and crop management practices. It focused on the global soil quality impacts of producing feed for pigs raised in Brittany, France, with ingredients (maize, wheat, triticale, barley, pea, rapeseed meal, soya meal and oil and cane molasses) coming from Brittany, Brazil and Pakistan (Table 2). Since the method requires data as precise as possible, we obtained regional data for agricultural practices in France (Brittany) and Brazil (Santa Catarina) using an INRA LCA database (UMR SAS, Rennes, France) and commercial and online sources (details in Electronic Supplementary Material, Table 3). We assumed typical management practices and crop yields equal to 5-year means. For sugarcane, harvested annually but planted once every 6 years, the impacts of the tillage and sowing operations needed to establish it were divided by six. Soil data came from the Harmonized World Soil Database (FAO et al. 2009). Climate data came from Météo France for France and EPAGRI (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina) for Brazil (Vamilson Prudêncio da Silva, personal communication). Pakistani climate data were acquired from international climate databases (NASA 2012) for coordinates corresponding to the centre of the Punjab region (30°N, 70°E). For Pakistan, soil and climate characteristics were chosen from the centre of Punjab, the country's main production zone of sugarcane. Economic allocation (with prices averaged over 2004–2007) was used to allocate impacts of canola, soya and sugarcane to canola meal, soya meal and oil and molasses, respectively. Impacts per tonne of ingredient in pig feed were added together to calculate total impact per tonne of pig feed produced in Brittany.

3 Results

The total area affected per hectare by compaction was similar for crops grown in Brittany (19,620–20,690 m^2/ha) due to similar tillage practices (see Table 2). In the topsoil, maize production caused the largest loss of pore volume per hectare (185.2 m^3/ha). For crops in loamy soils, topsoil losses of pore volume per hectare tended to be three times those in the subsoil, except for canola (topsoil/subsoil ratio of 3.4 instead of 3.0). For soya, the only crop in a clayey soil, the ratio was lower (2.4). The range of pore volume losses per hectare tended to be small for the crops grown in Brittany (171–185 m^3/ha), and the pore volume losses per tonne of crop were inversely proportional to yields. For pig feed ingredients, the relative impact of each ingredient tended to be proportional to its relative mass in the feed.

Predicted impacts in Brittany, France, were consistent with the machinery used there for each crop type. For example, maize operations need heavier tractors with wider wheels than those for winter cereals, but they pass less often over the field. In Santa Catarina State, Brazil, reduced tillage is used, decreasing the number of machine operations and therefore, potentially, the impact. In Brittany, field operation dates for maize have a high probability of occurring during periods when its loamy soils have relatively high water content. In contrast, the clayey soils underneath Brazilian soya compact less, even though machines used for soya are heavier than those used for maize. In Pakistan, planting sugarcane only once every 6 years decreases the compaction impact of planting over the life cycle of the crop. Of the six terrestrial operations considered for sugarcane cultivation (Electronic Supplementary Material, Table 3), the impacts of the first five are divided by six (crop establishment), three are not considered because they are made by plane. For rapeseed, operation dates correspond to periods of drier soil in Brittany, decreasing stress propagation, and thus compaction, in the soil.

4 Sensitivity analysis

A "one-factor-at-a-time" sensitivity analysis was performed to estimate the relative sensitivity of predictions of pore volume loss per hectare due to production of a single crop (maize) to individual variations in soil type (loam vs. clay), initial bulk density and gravimetric water content. Sensitivity was measured with a sensitivity index, calculated by dividing the normalised range of output values by the normalised range of the associated input values. The sensitivity analysis showed that loss of pore volume was more sensitive to initial bulk density and water content in loamy soils than clayey soils. Overall, sensitivity to initial bulk density increases as soil water content increases, and sensitivity to soil water content increases as initial bulk density decreases (Fig. 3). Future sensitivity analyses can be done for other factors, such as machine mass and width, tillage practices for different type of location and humidity.

5 Discussion

The compaction indicator is currently restricted to life cycle stages of agricultural production that involves machine field operations. The trends in comparisons of potential compaction estimates are consistent with general experimental observations: compaction due to traffic increases with soil moisture up to a specific water content and depends on the

Table 2 Key data and predicted topsoil (0–30 cm), subsoil (30–50 cm) and total (0–50 cm) compaction impacts for farm gate crops (per hectare and per tonne), products made from them (per tonne) and a representative feed production for pig raised in Brittany, France, that uses the crop-based products as ingredients (per tonne)

Crop		Unit	Maize	Wheat	Triticale	Barley	Pea	Canola	Soya		Sugarcane	
Origin			Brittany, France	Brittany, France	Brittany, France	Brittany, France	Brittany, France	Brittany, France	Santa Catarina, Brazil		Punjab, Pakistan	
Soil texture			Loam	Loam	Loam	Loam	Loam	Loam	Clay		Loam	
Tillage practice			Tillage	Tillage	Tillage	Tillage	Tillage	Tillage	Reduced tillage		Tillage	
Total soil area compacted		m^2/ha	19,620	20,690	20,690	20,690	20,036	20,114	15,976		11,566	
Loss of pore volume	Topsoil	m^3/ha crop	138.9	128.2	128.2	128.2	135.2	137.5	96.9		95.4	
	Subsoil		46.3	43.2	43.2	43.2	43.2	40.8	40.1		32	
	Total		185.2	171.4	171.4	171.4	178.4	178.3	137.0		127.4	
Yield (dry matter)		t/ha	9.0	7.0	7.0	6.5	4.2	3.3	2.8		35.0	
Total soil area compacted		m^2/t crop	2,180	2,956	2,956	3,188	4,805	6,095	5,706		901	
Loss of pore volume	Topsoil	m^3/t crop	15.4	18.3	18.3	19.7	32.2	41.7	34.6		2.7	
	Subsoil		5.1	6.2	6.2	6.6	10.3	12.4	14.3		0.9	
	Total		20.6	24.5	24.5	26.4	42.5	54.0	48.9		3.6	
Crop-based product			Maize	Wheat	Triticale	Barley	Peas	Canola meal	Soya meal	Soya oil	Molasses	Feed total
Economic allocation		%	100	100	100	100	100	23.8[a]	65.4[a]	34.6[a]	18.1[a]	
Loss of pore volume	Topsoil	m^3/t product	15.4	18.3	18.3	19.7	32.2	16.4	28.5	63.6	10.2	
	Subsoil		5.1	6.2	6.2	6.6	10.3	4.9	11.8	26.3	3.4	
	Total		20.6	24.5	24.5	26.4	42.5	21.3	40.3	89.9	13.5	
Pig feed ingredient		% by mass	3.1	34.5	14.6	4.3	16.3	8.8	7.8	1.1	3.6	94.2[b]
Loss of pore volume	Topsoil	m^3/t feed	0.48	6.32	2.68	0.86	5.30	1.44	2.22	0.71	0.37	20.38
	Subsoil		0.16	2.13	0.90	0.29	1.69	0.43	0.92	0.29	0.12	6.93
	Total		0.64	8.45	3.58	1.15	6.99	1.87	3.13	1.00	0.49	27.30
Topsoil/subsoil compaction ratio			3.0	3.0	3.0	3.0	3.1	3.4	2.4	2.4	3.0	3.0

[a] Economic allocation based on mean prices from 2004 to 2007 (ISTA 2009)

[b] The total of percentages does not equal 100 % because ten ingredients, each representing less than 1.1 % of the feed by mass, were excluded

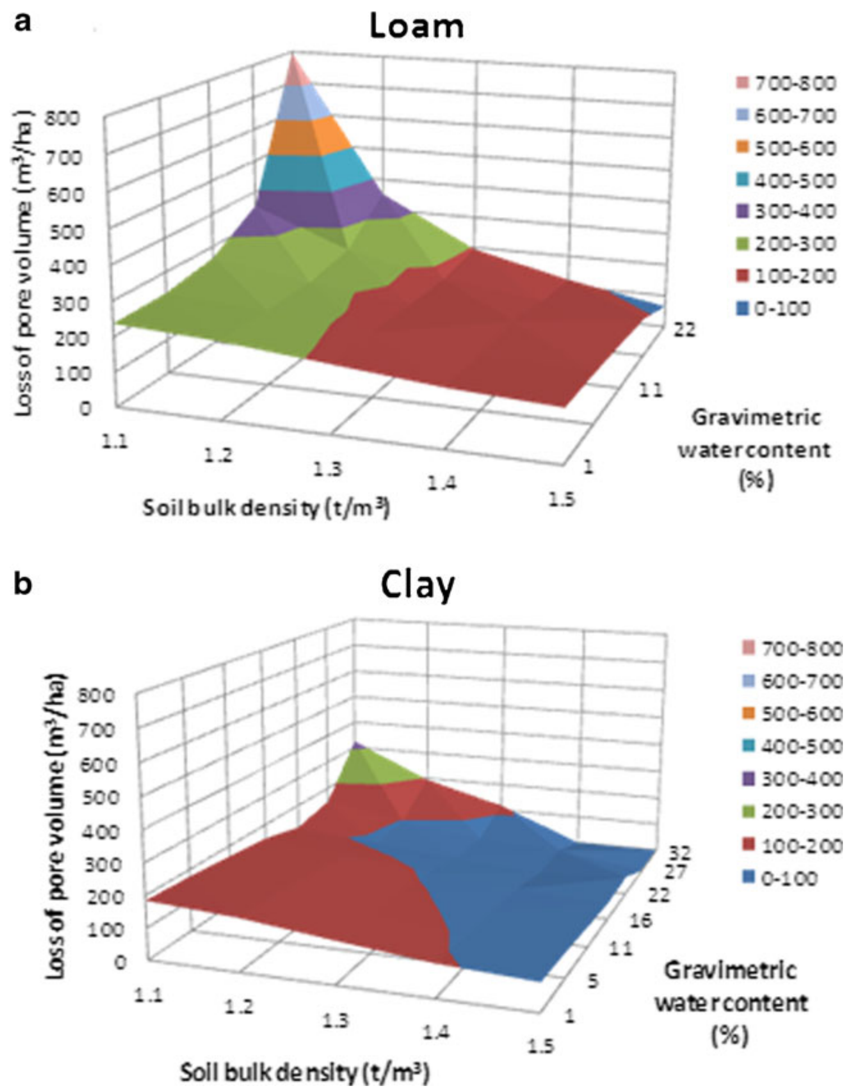


Fig. 3 Sensitivity of loss of pore volume (in cubic metre) in soil due to machine traffic to produce grain maize in Brittany, France, to initial soil bulk density (in tonnes per cubic metre) and gravimetric water content (in percent) for **a** loam or **b** clay soil. Note that maximum soil water content changes with soil type

mass and tyre width of the machinery used (Richard et al. 1999), soil type, tillage management and climate (Boizard et al. 2001). Although the COMPSOIL model has been validated only for moderate loads on sandy loam and clay loam soils (O'Sullivan et al. 1999), its function within the method is to identify any relative differences in compaction impact between scenarios, not to make highly accurate bulk density predictions. The sample case study, quantifying pore volume loss due to production of different crops in different countries, shows the feasibility of the method at different levels of data availability (high for France, medium for Brazil and low for Pakistan).

Many of the necessary input data (e.g. agricultural practices, field operations, operation dates) are standard input data for crop LCAs. Data about agricultural machines (e.g. mass, tyre width, operating width) may be more difficult to find, but many can be found online. The data collected for this research form one such database. We believe that the method reaches a balance between being overly complex and overly simple. Simplifications include assuming uniform water content and bulk density profiles and, for most operations in a sequence, the same initial bulk density. The uniform bulk density profile may not represent physical reality, but this simplification seems acceptable given uncertainty and lack of knowledge about changes in bulk density with depth and the fact that the indicator aggregates bulk density changes throughout the profile. The use of COMPSOIL model depends on the soil type. The model requires a stress/strain relationship and mechanical soil parameters and their variations as a function of a variety of physical properties. The constants for estimating soil parameters of model equations are given by O'Sullivan et al. (1999) for sandy loam and clay loam and by Défossez et al. (2003) for loess and calcareous soil. Saffih-Hdadi et al. (2009) gives pedotransfer functions of representative soils covering the soil texture triangle.

In addition, BILHY, developed to identify soil water deficits, cannot simulate water contents greater than field capacity,

such as saturated soil. Replacing the two-compartment model of soil water content with a two-dimensional soil model could predict the soil water profile more precisely (i.e. every 5 cm), but the added complexity may not result in greater accuracy. Studies indicate that an increase in model realism may not only fail to increase model accuracy, but may decrease it (and model generality, as well) (Weisberg 2006). Water content in the first few centimetres of soil may greatly influence rutting and compaction impacts because that is where wheels contact the soil, but the extra parameters required to simulate two-dimensional water flow, and the uncertainty around them, do not currently warrant burdening the method with further input data requirements. Nonetheless, the compaction indicator currently considers only a cumulative and negative impact. The indicator could be expanded to consider a positive impact of ploughing on soil pore volume, balanced with a negative impact on long-term soil structure. The compaction indicator could also be expanded by considering compaction due to livestock trampling and the impact of climate on compaction resilience and on bare soil. The long-term cropping impact could be considered, for example, by setting initial soil conditions as a function of previous tillage practices or considering the impact of alternating root systems of different depths. Each of these improvements would require additional research. COMPSOIL does not explicitly consider the influence of SOM content on compaction, but the framework (Garrigues et al. 2012) already includes indicators of SOM change and erosion to assess impacts on soil quality (Corson 2012). All three indicators can be used in LCAs of bio-based materials, for example to compare cropping or waste management techniques, such as composting. Although the impact of non-cultivation processes on soil quality could be included, many of them, such as soil sealing with concrete, transform soil into nonsoil, which has zero soil quality. Thus, we believe that non-agricultural processes are better included with impacts of land use and land use change. The soil quality impact indicators can interact with other impact categories, such as climate change, in which SOM changes influence net C emissions into the atmosphere, and eutrophication and biotic production, which are influenced by erosion. Also, soil quality impact indicators complement other impact categories, providing increased ability to identify "burden shifting" or trade-offs between transport distance and soil quality. All the input data necessary for establishing the LCI for the three indicators (approximately 30 parameters) are presented in the project report (Corson 2012). Most input data are common to the three indicators, and the inclusion of new soil quality impact indicators (such as salinisation) should only slightly increase input data requirements. The soil compaction indicator could be linked to midpoint/endpoint indicators in the future by specifying impact pathways between a change in soil porosity and water infiltration, gas exchange with the atmosphere, and biological processes.

6 Conclusions

Impacts on soil quality should be taken into account into a life cycle perspective because of the essential role of soils in ecosystem functioning. Integrating soil quality impacts throughout the life cycle of an agricultural product requires a global approach to assess impacts on soil quality that can be adapted to individual soil and climate contexts. We have developed a framework for quantifying indicators of impact on soil quality, valid for all soil and climate conditions, and considering both on-site and off-site agricultural soils. These indicators can be used in LCAs of bio-based materials or the waste management stage that considers composting. Soil compaction has not been quantified in detail in LCA. Total compaction impact results from the combination of soil, climate and management characteristics and is expressed as a loss of pore volume (in cubic metre/FU). Most input data can be found in existing national and international databases, except for some agricultural practices, which vary widely by region.

The method aggregates compaction impact of all crop-based ingredients in different soil and climate conditions. Estimates of compaction impact are consistent with empirical observations, increasing with soil water content and depending on soil type and machine mass and tyre width. Within a soil type, compaction predictions are most sensitive to initial bulk density and soil water content.

The method developed answers needs identified by Garrigues et al. (2012) for LCA indicators of impacts on soil quality. The framework allows for incremental improvement, for example by refining the initial state of the soil as a function of previous tillage practices. The method currently considers only compaction due to agricultural machines, but other causes of compaction could be added (e.g. animal trampling) if the addition is simple enough to be used by non-experts, general enough to parameterise with available data at a global scale and sufficiently validated.

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